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RELAXATION OF RESIDUAL STRESSES WHEN EXTRACTING A SPECIMEN FROM A DISSIMILAR METAL ELECTRON BEAM WELDED PLATE

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ABSTRACT

To study the extent of residual stress relaxation and characterise the final residual stresses, neutron diffraction measurements and three-dimensional finite element analysis were conducted on a compact tension, C(T) specimen. The specimen was extracted from a dissimilar metal electron beam (EB) welded plate, in the as-welded condition. This was done as a preliminary step to examining crack growth and fracture of a C(T) specimen subjected to applied loads in the presence of residual stresses. The dissimilar metal weld was made from austenitic AISI 316LN stainless steel and a ferritic/martensitic P91 steel, using the EB welding process. The C(T) specimen was extracted from the sample plate using wire-cut electron discharge machining (EDM). The specimen was then measured on the neutron strain diffractometer, E3, at the Helmholtz Zentrum Berlin (HZB), in Germany. A finite element model was created using the ABAQUS code to simulate the extraction of the specimen from the welded plate, predict the residual stress relaxation and compare with measurements. This paper presents the details of the specimen extraction, the neutron diffraction experiments and the finite element model. The predicted and the measured residual stresses, after specimen extraction are compared with the as-welded residual stresses and the extent of stress relaxation quantified.

Key Words: Residual stress, stress relaxation, electron beam welding, dissimilar metal weld

1.0 INTRODUCTION

Fracture toughness assessment of engineering components is of great importance from a structural integrity point of view [1 - 5]. To measure the fracture toughness properties, C(T) specimens are often extracted from a component or a weld pad. However, in most cases the existing residual stress state in these C(T) specimens remains unknown. The residual stresses retained in the C(T) specimens can have a significant influence on the measurement of fracture toughness of the material, particularly if the C(T) specimens are extracted from weld pads without any post-weld stress relieving treatment.

In the current paper, the research work undertaken to determine the residual stresses retained in a C(T) blank specimen, extracted from a dissimilar metal weld fabricated using the EB welding process, prior to the introduction of crack, through measurements and finite element predictions, is presented. The details of the neutron diffraction experiment to measure the retained residual stresses are explained. The finite element model created to simulate the specimen extraction from the weld pad and predict the residual stress relaxation is described. The final residual stresses in the component, from the measurements and predictions are compared with the as-welded stresses in the weld pad and the extent of relaxation is determined.

2.0 SAMPLE DETAILS

The dissimilar metal weld was made from modified 9Cr-1Mo (P91), a ferritic/martensitic steel joined to AISI 316LN austenitic stainless steel, using EB welding. The dimensions of the weld pad were 250 mm x 156 mm x 11 mm. The width of the fusion zone was approximately 1.3 mm and that of the HAZ was 0.7 mm. The welding process was autogenous, without the addition of any filler material. After the welding pass, an additional cosmetic/smoothing pass was introduced using a defocussed beam with 26 mA and 100 kV which resulted in a penetration depth of 4.5 mm. The purpose of the smoothing pass was to enhance the surface finish and to minimise any post weld machining processes. The residual stress profile from the welding process was characterised using neutron diffraction and finite element analysis. The particulars of the welding process and residual stress characterisation are explained elsewhere in detail [6, 7].

A C(T) sample measuring 40 mm x 38 mm x 11mm was extracted from the dissimilar metal weld pad using an EDM process. A schematic diagram indicating the location of C(T) blank specimen is shown in Fig. 1.

3.0 NEUTRON DIFFRACTION EXPERIMENT

In order to measure the residual stresses in the C(T) blank specimen, neutron diffraction measurements were conducted on the instrument E3, at the HZB facility in Berlin. The instrument is a monochromatic strain diffractometer with one detector bank. For measuring the stress-free lattice spacing, two sets of d_0 samples were manufactured from the weld pad. The schematic of the reference samples along with the measurement line is shown in Fig. 2. A 2 mm slice was machined from one of the ends of the weld plate using EDM. Two match-stick samples were extracted from the far field regions on either side of the slice to act as reference samples for each of the materials respectively. A comb sample was extracted from the upper half of the weld fusion zone as a reference sample for the weld fusion and HAZ regions.

The measurements were made approximately at mid-thickness of the plate. The line of measurement was chosen such that it was 2 mm away from the crack tip and is shown in Fig. 3. Because of the narrow fusion width, steep gradients of stress were expected across the weld and also the stress state was believed to be highly triaxial. To capture such steep gradients in stress over a small length scale, a smaller gauge volume of 0.5 mm x 2 mm x 2 mm was employed. The lattice spacing was measured in all the three principal stress directions on the C(T) blank as well as the reference specimens. The measurements were made on the (311) plane and (211) plane for the austenitic and ferritic phases respectively. The weld fusion zone contained material from both the phases and the detector angle was wide enough to capture the reflections from the lattice planes corresponding to both the phases in a single set-up.

From the measured lattice spacing the strains were calculated using the relation [8, 9]

$$\varepsilon_x = \frac{d_x - d_{0x}}{d_{0x}} \qquad (1)$$

where ε_x is the strain in x-direction, d_x, d_{0x} are the lattice spacing in x-direction in the C(T) blank and the stress-free reference sample respectively.

The stresses were determined using the eq. (2) [8, 9]

$$\sigma_x = \frac{E}{(1+\nu)}[\varepsilon_x + \frac{\nu}{(1-2\nu)}(\varepsilon_x + \varepsilon_y + \varepsilon_z)] \quad (2)$$

where σ_x is the stress in x-direction, E is the Young's modulus, ν is the Poisson's ratio. These values were considered from the Kroner's recommendations for bulk properties of poly-crystals for bcc and fcc phases respectively [9].

3.0 FINITE ELEMENT ANALYSIS

A three-dimensional finite element analysis was conducted using ABAQUS 6.14 code to predict the residual stress relaxation in the C(T) blank specimen. The FE model of the EB welding process on the dissimilar metal plates was developed and the residual stresses were predicted. The predicted final residual stress state on the weld pad from the welding process, were mapped on to the FE model to predict the residual stress relaxation in the C(T) blank specimen. The details of the FE model of the welding process and the residual stress predictions were described in detail elsewhere [6, 7].

The FE model consisted of first order hexahedral 3D stress elements (C3D8R). The removal of the material from the EDM process was simulated using the ABAQUS key word *Model Change [10, 11]. The material removal was simulated using a total number of 78 steps. During each step the elements corresponding to the material removed were deactivated in the model. The tensile properties and the stress-strain data for both the materials were obtained from the literature. The stress relaxation from the material removal was predicted as an output.

4.0 RESULTS AND DISCUSSION

The longitudinal residual stress (parallel to the direction of welding) in the C(T) blank specimen from the measurements and predictions on the measurement line is shown in Fig. 4. It can be seen that the measurements and the predictions are in good agreement. Even after the stress release from machining, a peak stress of ~ 300 MPa is observed at a distance of ~ 2 mm from the weld centerline on the P91 side. Also the weld fusion zone has a compressive stress of ~ 300 MPa, as a result of solid state phase transformation experienced by P91 steel during rapid cooling.

The measured longitudinal residual stress in the C(T) blank specimen is compared with the as-welded residual stress in the weld pad and is shown in Fig. 5. It can be seen clearly that there is a considerable amount of stress-relaxation in the C(T) blank specimen compared to the weld pad due to the machining process. However a significant portion of stress is still retained in the blank even after machining. The magnitude of the residual stress in the transverse and the normal directions was also considerable in magnitude making the final residual stress state in the C(T) blank specimen highly triaxial. Therefore, it is essential to characterise these stresses before performing any fracture tests.

5.0 CONCLUSIONS

Based on the research conducted on the C(T) blank specimen extracted from an EB welded dissimilar metal weld pad, the following conclusions can be drawn:

1. Although the creation of a C(T) specimen of smaller size than the parent plate has considerably relaxed the residual stresses, there is still a significant portion of the original stresses remaining in the C(T) blank.
2. The final residual stress state in the C(T) blank is compressive in the weld fusion zone due to phase transformation effects of P91 steel. Also the residual stress state is highly triaxial even after the relaxation.
3. The measurements and predictions of the residual stresses in the C(T) blank agree well validating the numerical model.

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REFERENCES

1. Y. Traore, S. Paddea, P.J. Bouchard, M.A. Gharghouri, *Experimental Mechanics* (2013), **53(4)** 605.
2. F.Hosseinzadeh, P.J. Bouchard, J.A. James, *Material Science Forum* (2010), **652**, 210.
3. S. Hossain, C.E. Truman, D.J. Smith, R.L. Peng, U. Stuhr, *International Journal of Solids and Structures*, **44** (2007), 3004.
4. C. Faidy, In Proceedings of *ASME Pressure Vessel and Piping Conference*, USA, (2008).
5. R.J.A. McCluskey, *Residual stress effects on the fracture toughness behaviour of a narrow-gap austenitic stainless steel pipe weld*, PhD Thesis, University of Manchester, UK, (2012).
6. K. Abburi Venkata, *Characterising high energy beam welding in structural steels with numerical simulation and validation*, Solid Mechanics Research Group, Department of Mechanical Engineering, University of Bristol, UK, (2015).
7. K. Abburi Venkata, C.E. Truman, D.J. Smith, Proceedings of the fourteenth *International conference on Pressure Vessel Technology*, Shanghai, (2015).
8. M.E. Fitzpatrick, A. Lodini, *Analysis of residual stress by diffraction using neutron and synchrotron radiation*, Taylor and Francis Group, (2003).
9. T.M. Holden, M.T. Hutchings, P.J. Withers, T. Lorentzen, *Introduction to the characterisation of residual stresses by neutron diffraction*, CRC Press, (2005).
10. L-E. Lindgren, *Journal of Thermal Stresses*, **24**, (2001), 195.
11. M. Barge, H. Hamdi, J. Rech, J-M. Bergheau, *Journal of Materials Processing Technology*, **164 - 165**, (2005), 1148.

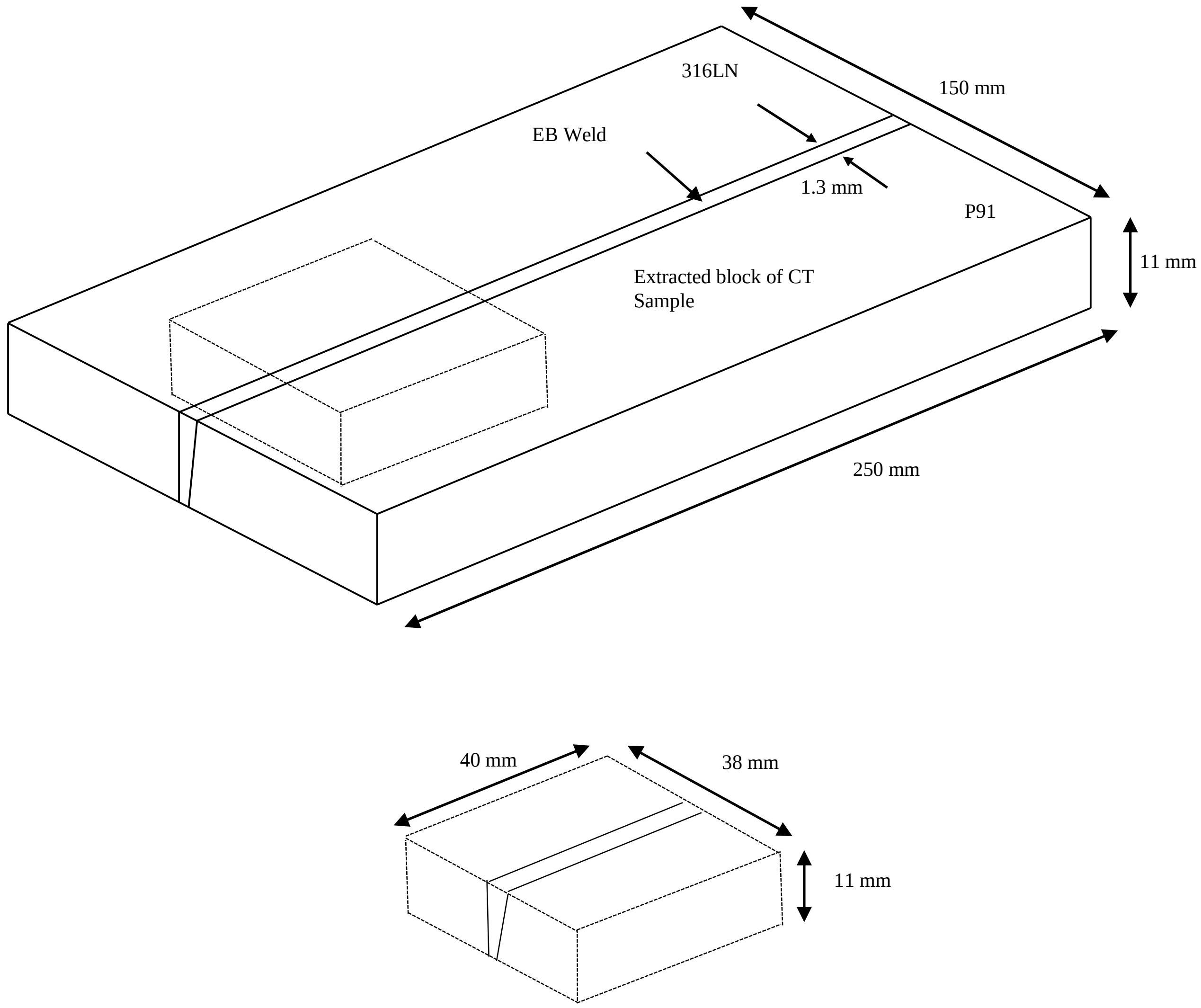

Fig. 1. Schematic of the dissimilar metal weld pad and C(T) specimen

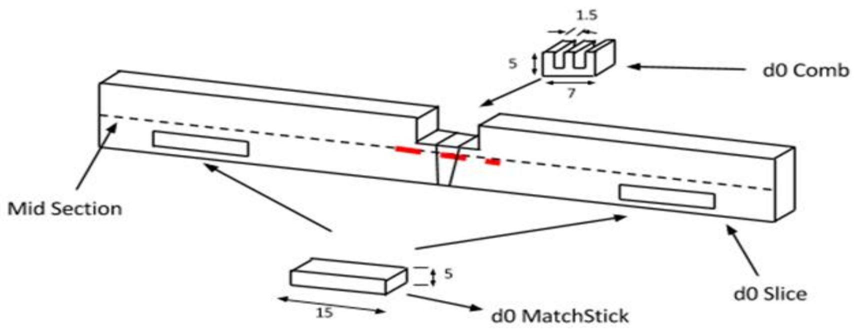

Fig. 2. Schematic of the d_0 specimens

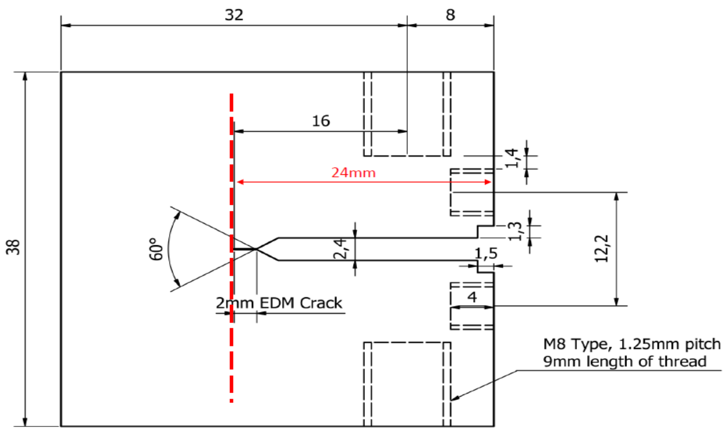

Fig. 3. Schematic depicting the measurement line for neutron diffraction experiment

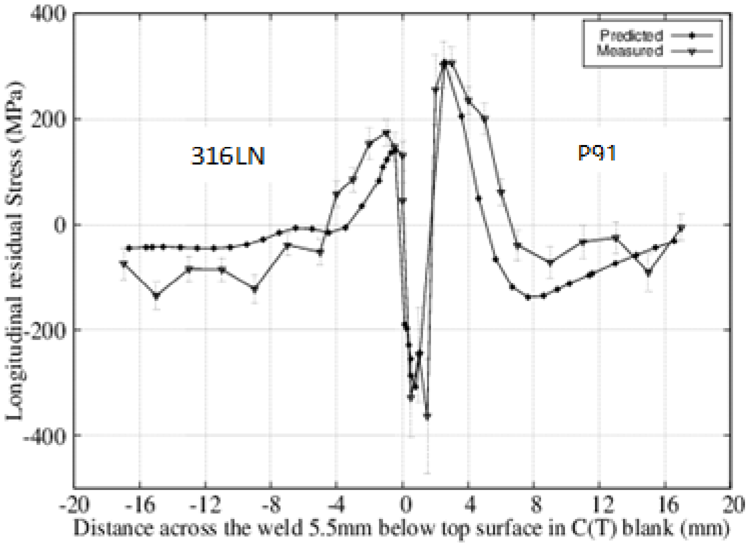

Fig. 4. Comparison of the measured and predicted residual stresses in the C(T) blank specimen

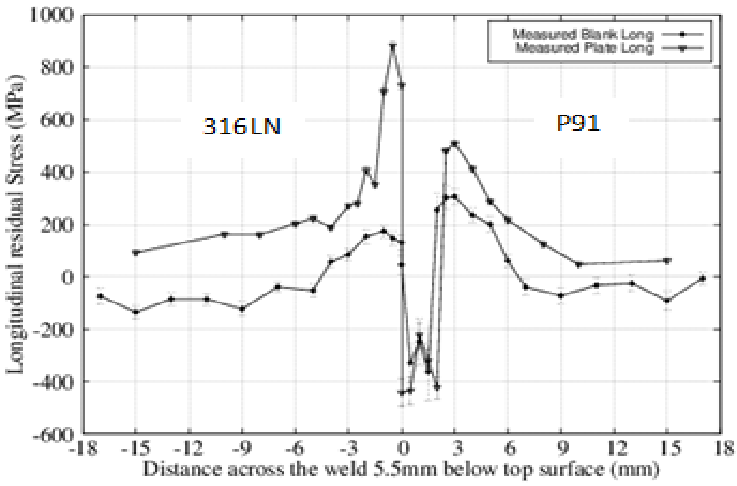

Fig. 5. Comparison of the measured longitudinal residual stress in the as-welded sample plate and C(T) blank